DEVELOPMENT OF A UNIFIED CONSTITUTIVE MODEL FOR AN ISOTROPIC NICKEL BASE SUPERALLOY RENÉ 80

V.G. Ramaswamy, R.H. Van Stone, J.H. Laflen
General Electric Company
Cincinnati, Ohio 45215

D.C. Stouffer
University of Cincinnati
Cincinnati, Ohio 45221

Accurate analysis of stress-strain behavior is of critical importance in the evaluation of life capabilities of hot section turbine engine components such as turbine blades and vanes. The constitutive equations used in the finite element analysis of such components must be capable of modeling a variety of complex behavior exhibited at high temperatures by cast superalloys. The classical separation of plasticity and creep employed in most of the finite element codes in use today is known to be deficient in modeling elevated temperature time dependent phenomena. Rate dependent, unified constitutive theories can overcome many of these difficulties. A new unified constitutive theory was developed to model the high temperature, time dependent behavior of Rene' 80 which is a cast turbine blade and vane nickel base superalloy. Considerations in model development included the cyclic softening behavior of Rene' 80, rate independence at lower temperatures and the development of a new model for static recovery.

EXPERIMENTAL PROGRAM

The constitutive behavior of Rene' 80 under a multitude of conditions was experimentally determined.The test specimens, experimental temperatures, strain ranges, strain ratios, hold times, and strain rates were established through an evaluation of the operating conditions in commercial jet engines. In performing the experiments, the approach was to evaluate a series of transient and steady state conditions in each test by using a block cycling method. By using several combinations of strain range blocks in different sequences in a single experiment all combinations of transient effects could be interrogated. The block length was selected to produce cyclically stable hysteresis loops by the end of each block. The experimental results of each test were automatically saved in digitized form in real time by using a data acquisition device. These final data files could then be used in plotting data or determining constants in constitutive theories.

THEORY DEVELOPMENT

Following a detailed review, the Bodner model [1] and a generic back stress/drag stress model [2] were selected for further detailed evaluations with the Rene' 80 data. Many of the results from that study have been presented previously [2]. It was found that neither model was adequate for predicting the response characteristics of Rene' 80 at 1800F. Consequently a new theory was developed which combined the Bodner exponential flow law with a back stress formulation. It was found to be necessary to modify the evolution equations for the back stress to account for static recovery effects and to account for effects in the small inelastic strain regime. When these factors were included the final set of equations could be written as:

$$\dot{\epsilon}_{ij}^{I} = D \exp\left[-\frac{A}{2} \left(\frac{Z^2}{3K_2}\right)^n \frac{(S_{ij} - \Omega_{ij})}{\sqrt{K_2}} \right] \tag{1}$$

$$K_2 = 1/2 (S_{ij} - \Omega_{ij})(S_{ij} - \Omega_{ij}) \tag{2}$$

$$\Omega_{ij} = \frac{G}{E} S_{ij} + \left(1 - \frac{G}{E}\right) \Omega_{ij}^{I} \tag{3}$$

$$\dot{\Omega}_{ij}^{I} = f_1 \dot{\epsilon}_{ij}^{I} - \frac{f_1}{\Omega_s} \Omega_{ij} \dot{R} \tag{4}$$

$$\dot{Z} = m(z_1 - z) \dot{W}^{I} \tag{5}$$

$$\dot{\Omega}_s = -B(\sigma_e/\sigma_0)^r (\Omega_s - \Omega_{sat}) \tag{6}$$

where
$$\dot{R} = \sqrt{\frac{2}{3} \dot{\epsilon}_{ij}^{I} \dot{\epsilon}_{ij}^{I}}, \quad \Omega_s(o) = \Omega_{max}, \quad \Omega_{ij}^{I}(o) = 0, \quad z(o) = Z_0$$

The procedures for determining the constants in these equations have been reported previously in [2,3]. Basically it involves the determination of most of the constants through the use of the monotonic, strain rate dependent, stress-strain curves; only the saturated value of the drag stress, Z1, and the rate of softening parameter, m, are determined from cyclic tests. The accuracy of these equations. has been verified very extensively through comparisons with a wide variety of experimental data . Figures 1 and 2 show the correlation of the monotonic stress-strain data at 1400F through 1800F, respectively. That the theory is capable of predicting strain rate dependent as well as rate independent behavior is clear.

Figure 3(a) shows a comparison with the first two cycles of a compressive mean strain test, while Figure 3(b) shows a comparison with the saturated hysteresis loop of this test. It has been seen that the theory can also predict the stress relaxation behavior at high and low temperatures. At 1400F Rene'80 exhibits stress relaxation, but no strain rate dependence. Creep capability comparisons are shown in Figures 4 and 5. These predictions depend strongly on the form of the static recovery term. Note that the form that is used in the current theory is much different than those used in other unified approaches.

Multiaxial capability verifications are shown in Figures 6,7 and 8. Figures 6 (a) and (b) show the axial and shear responses, respectively, for a combined tension/torsion (in-phase) test. Figure 7 shows the experimental results and theory predictions from a special nonproportional test where segments of proportional cycles were used . Comparisons of results from the first segment (cycle 5), and the last segment (cycle 32) of this nonproportional loading experiment are shown. That the predictions are accurate illustrates that the theory is good for such conditions without considering the additional hardening that has been found in some other materials. Figures 8 shows that the new theory can predict 90 deg. out-of-phase tension/torsion experimental results with good accuracy.

Figures 9 and 10 show two predictions of the theory with test data from combined temperature and strain cycling tests. The predictions are shown to be reasonable considering that the model development was based only on isothermal test data.

SUMMARY

A new multiaxial constitutive model which can represent the complex nonlinear high temperature behavior of Rene' 80 has been developed. The model was extensively verified based on experimental data at several temperatures. The TMF and nonproportional cyclic modeling capabilities of the model were demonstrated.

REFERENCES

1. Bodner, S.R. and Partom, Y., "Constitutive Equations for Elastic-Viscoplastic Strain Hardening Materials", ASME Journal of Applied Mechanics, 42, 1975.

2. Ramaswamy, V.G., Van Stone, R.H., Dame, L.T., and Laflen, J.H., "Constitutive Modeling for Isotropic Materials," NASA Conference Publication 2339, October 1984.

3. Ramaswamy, V.G., Van Stone, R.H., Dame, L.T., and Laflen, J.H., "Constitutive Modeling for Isotropic Materials", Annual Report, NASA CR17485, March 1985.
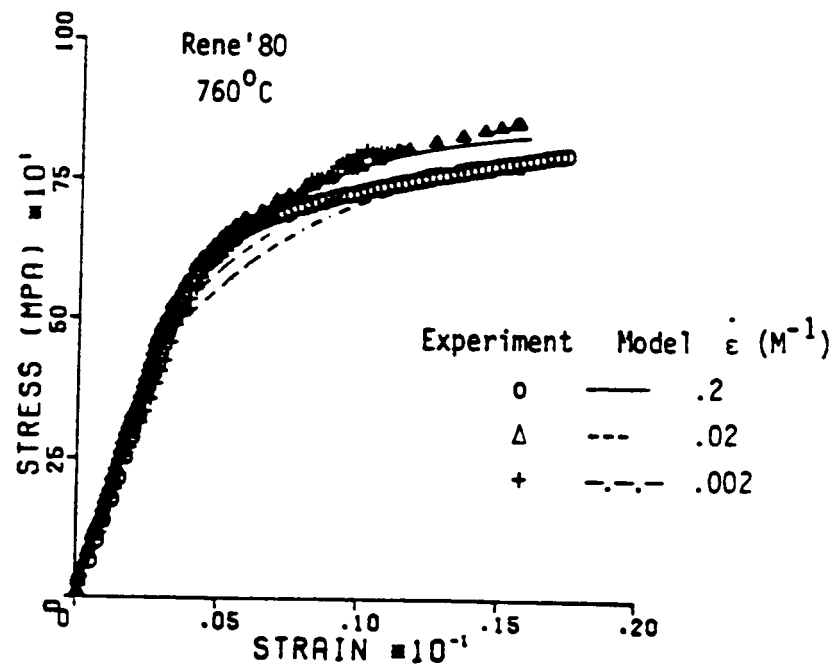
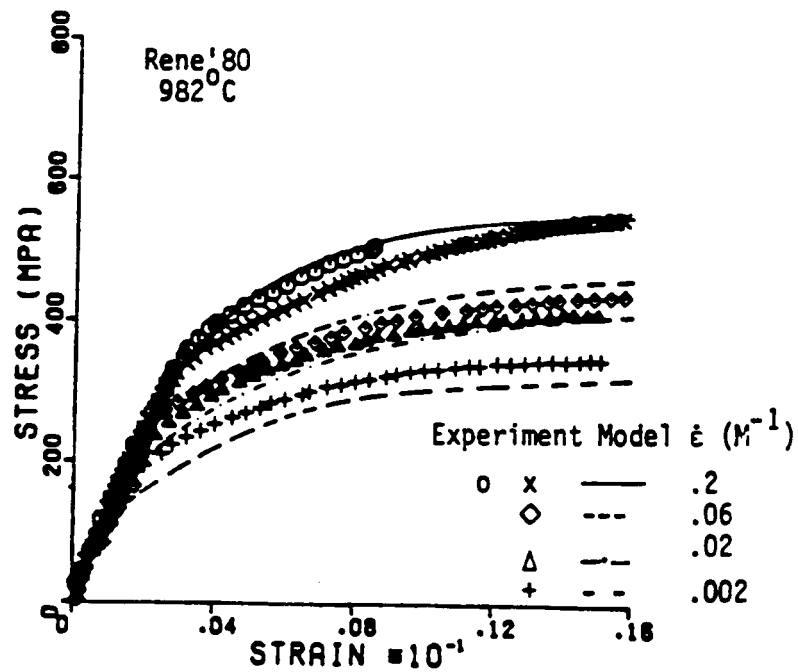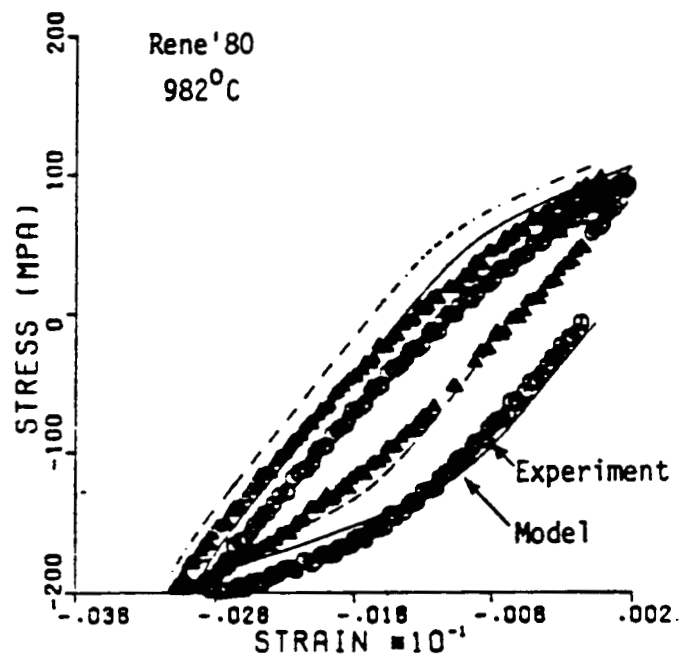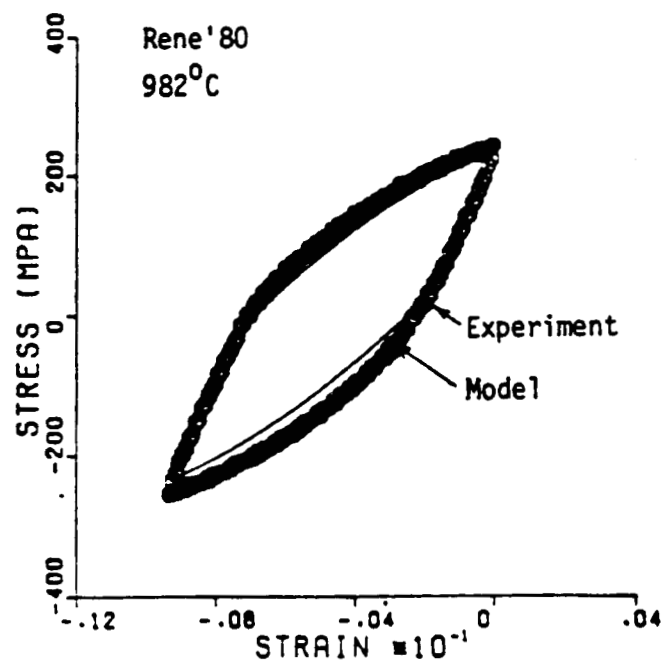Figure 1 Monotonic Tensile Response of Rene'80 at 760°C

Figure 2 Monotonic Tensile Response of Rene'80 at 982°C

(a) First Two Cycles

(b) Cycle 78

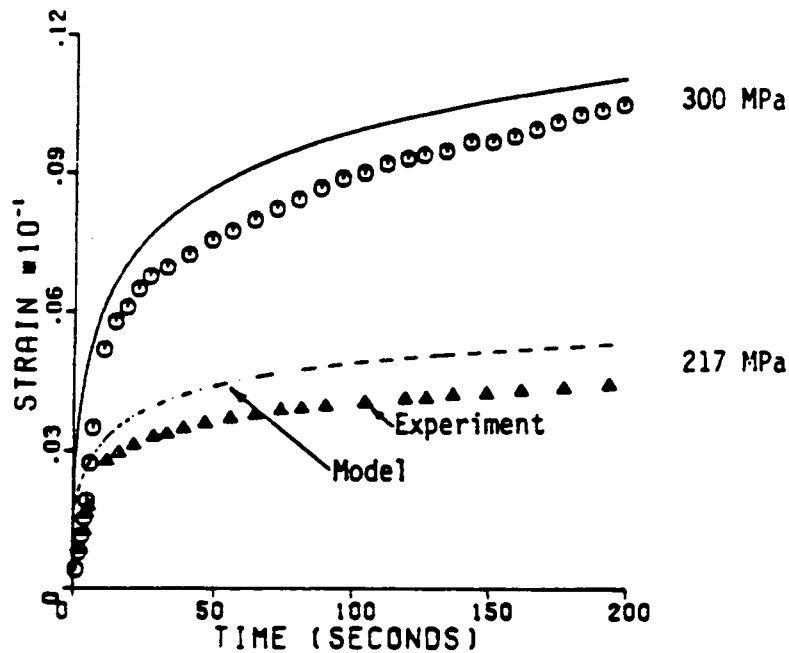Figure 3 Cyclic Response of Rene'80 with Mean Strain
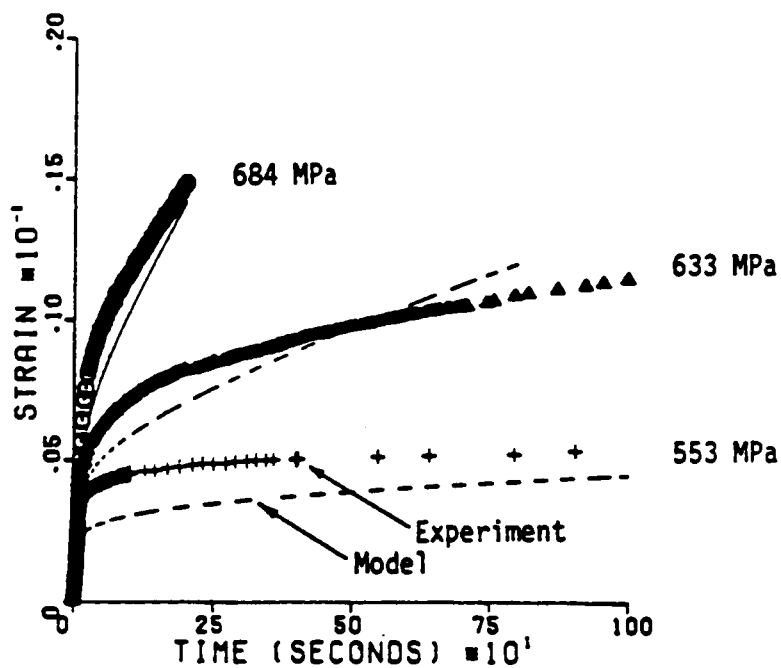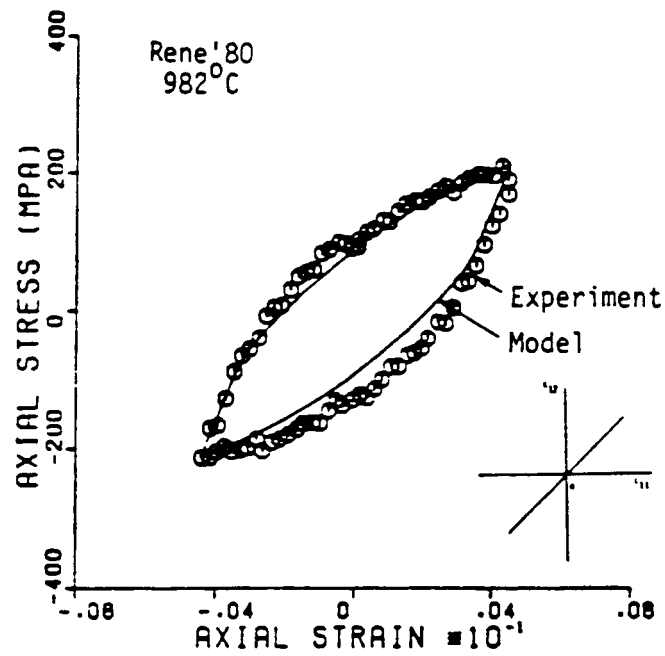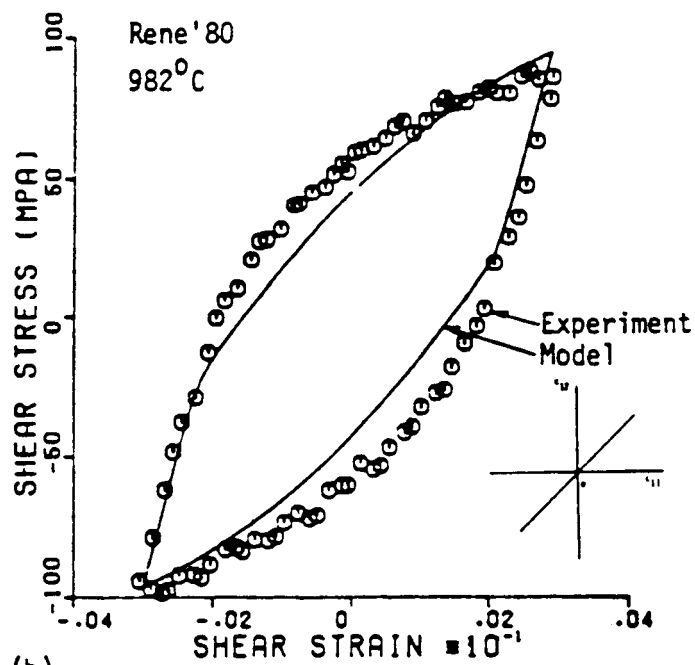
Figure 4, Creep Response of Rene'80 at 982°C

Figure 5 Creep Response of Rene'80 at 760°C

(a)

(b)

Figure 6   In phase Tension Torsion Cyclic
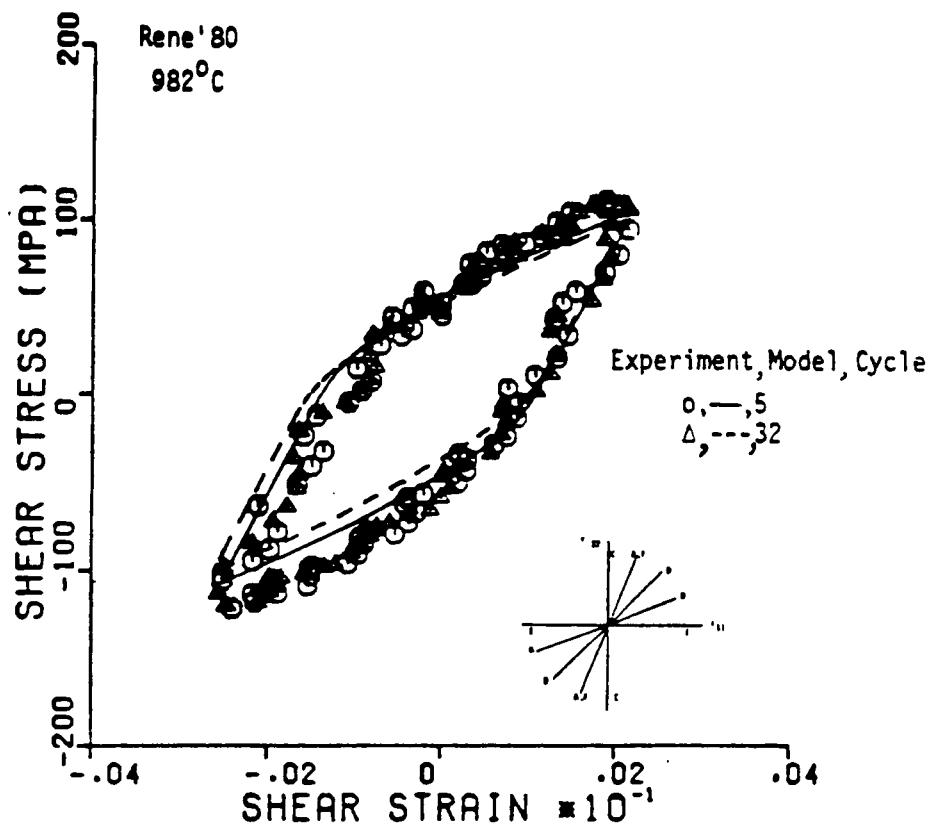Response of Rene'80 at 982°C, .002M^{-1}

Figure 7 Comparison of Rene'80 Response Before and
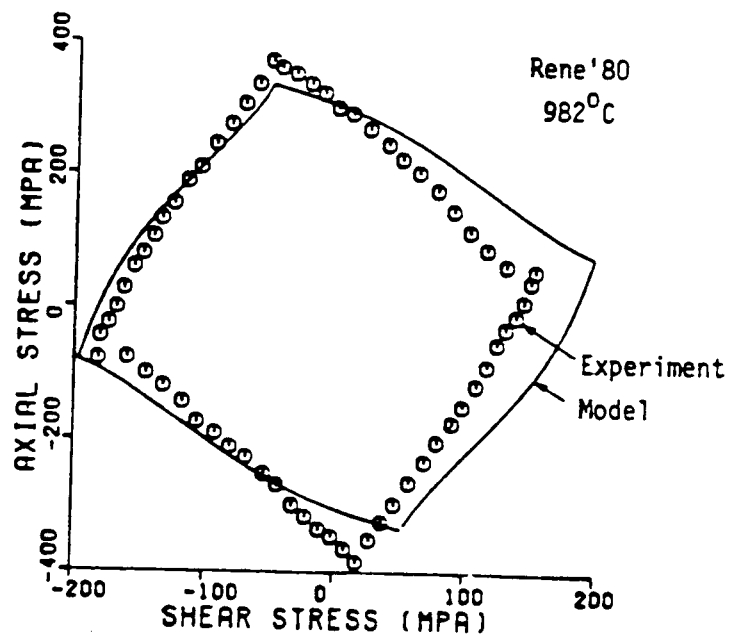After Non proportional loading (Paths A,F)

Figure 8 Rene'80 Response to 90° Out of Phase
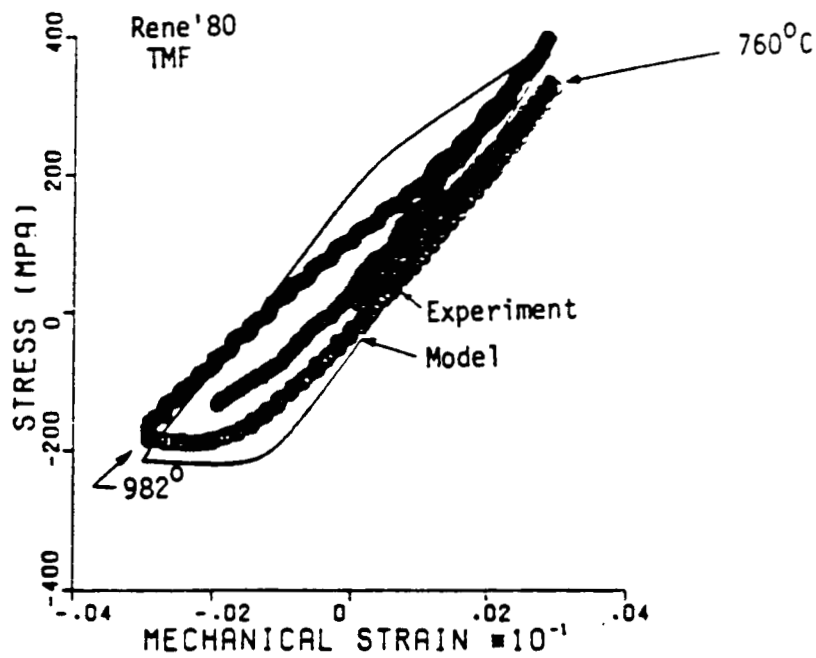Tension/Torsion Cyclic Loading
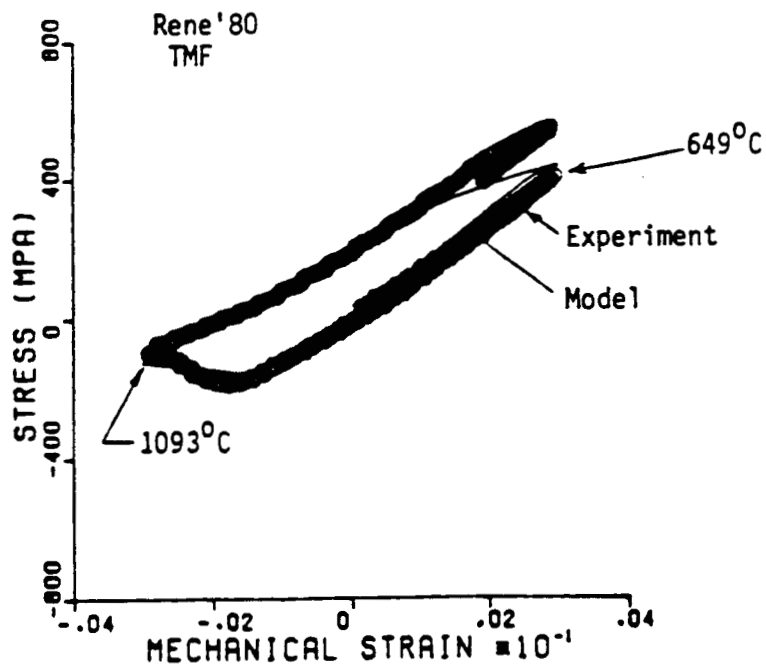
34

Figure 9   Rene'80 TMF Response (760°C-982°C Out of Phase)

Figure 10   Rene'80 TMF Response (649°C-1093°C Out of Phase)